JOURNAL OF PROPULSION AND POWER
Vol. 28, No. 2, March–April 2012

Effect of Large-Eddy Simulation Fidelity on Predicted Mechanisms of Jet Noise Reduction

Jeonglae Kim,* Daniel J. Bodony,† and Jonathan B. Freund‡
University of Illinois at Urbana–Champaign, Urbana, Illinois 61801

DOI: 10.2514/1.B34283

The aeroacoustic control of a Mach 1.3 turbulent jet demonstrates an unexpectedly subtle importance of accurate numerics for predicting and reducing turbulent jet noise. We observe that two nominally high-wave-number filters (as used to stabilize large-eddy simulations), one explicit that is optimized based upon an integral criterion and the other implicit with a tunable parameter, lead to significant changes in the near-field turbulence with concomitant changes in the acoustic field on the order of 2–4 dB. An apparent consequence is that an adjoint-based optimization procedure identifies different controls for the two simulated jets despite similar reductions of radiated sound. This suggests that sound-generating mechanisms of the Mach 1.3 turbulent jet may be more fundamentally modified by subtle changes in numerics than previously expected.

Nomenclature

c_∞ = ambient speed of sound
D = jet diameter
d = distance to a far-field point from nozzle exit
$\boldsymbol{F}$ = control to be optimized
J = transformation Jacobian
$\mathcal{J}$ = cost functional
n = azimuthal mode number
Pr = Prandtl number, $\mu C_p/k$
$\boldsymbol{Q}$ = vector of conserved flow variables
$\boldsymbol{q}$ = vector of primitive flow variables
$\boldsymbol{q}^\dagger$ = vector of adjoint flow variables
Re_D = Reynolds number, $\rho_j U_j D/\mu_j$
$r_{0.5}$ = jet half-width
St_D = Strouhal number, fD/U_j
U_j = nozzle-exit velocity
x_s = streamwise shifting parameter
μ_j = nozzle-exit viscosity
ρ_j = nozzle-exit density
φ = far-field angle with respect to downstream jet axis

I. Introduction

JET NOISE is an important factor in aircraft certification worldwide. Early work on jet noise focused on its parametric dependencies as determined through measurement [1–8] and on the theory of sound generation by turbulence [9–12] High-fidelity numerical simulations are capable of predicting the radiated noise from high-speed turbulent jets, [13–20] and are being used to improve Reynolds-averaged Navier–Stokes (RANS)-based noise prediction methods [21,22]. Results support the claim that by using large-eddy simulations (LES) or direct numerical simulations (DNS) we, as a community, can predict the radiated noise from high-speed turbulent jets issuing from round nozzles. Evaluating the noise prediction quality for more complicated nozzle geometries is ongoing.

Prediction is only a step, of course, toward the design of quieter jet engines. Continued increase of engine bypass ratios is no longer a viable option for reducing the engine's jet noise through corresponding reduction of the jet exhaust velocity. Instead, passive and active controls, either at the nozzle exit or further upstream, are being developed for jet noise reduction. However, it is also clear that this must be done without a burdensome performance penalty. Work at NASA [23] and elsewhere has shown that modest noise reduction can be achieved with nozzle-exit chevrons. Active flow strategies, such as arc-filament plasma actuators [24], have demonstrated noise reduction in preliminary, laboratory-scale experiments. The physical mechanisms behind the noise reduction remain unclear. They are believed to be tied to the development of streamwise vorticity, though a concrete link between vorticity modification and far-field sound remains elusive.

LES-based predictions of chevroned and actuated jets have not yet informed hypotheses explaining the noise reduction observed experimentally. For example, the impressively large simulation of a jet with nozzle chevrons by Uzun and Hussaini [25] suggests that still larger simulations of the brute-force approach are needed to make detailed predictions. The actuated jet simulations of Kim et al. [26] also did not provide conclusive data, since the simulated actuators were underresolved.

In this context, it stands to reason that LES-based predictions of turbulent jets involving passive and active noise control strategies are not soon going to represent in detail, even at the level of LES descriptions, all aspects of turbulence and its radiated sound. This is particularly important for the thin incoming boundary layer, its fluctuation statistics, and its response to actuation or nozzle geometric modifications. A substantial advance in computational resources seems necessary to "resolve away" this difficulty. Bodony and Lele [27] showed that exceedingly thick initial boundary layers or shear layers affect the radiated sound, a finding confirmed in a recent, more systematic study [20]. The effect of insufficient resolution might be amplified when seeking noise reduction strategies. This study shows how the choice of numerics, instead of the usually discussed choice of mesh size, can influence the change in the radiated sound from a high-speed turbulent jet. The results show in particular that the discretization can influence the change in the noise mechanisms when actively controlled.

II. Numerical Methods

A. Governing Equations

The compressible Navier–Stokes equations are solved in curvilinear coordinates. The basic equations for the conserved mass density ρ, momentum density ρu_i, and total energy density ρE are

Presented at the 49th Aerospace Sciences Meeting and Exhibit, Orlando, FL, 4–7 January 2011; received 14 March 2011; revision received 22 July 2011; accepted for publication 25 September 2011.

*Department of Mechanical Science and Engineering; kim208@illinois.edu. Student Member AIAA.
†Department of Aerospace Engineering. Senior Member AIAA.
‡Departments of Aerospace Engineering and Mechanical Science and Engineering. Associate Fellow AIAA.